Comparison of Observed Circulation Patterns and Numerical Model Predictions in Puget Sound, WA

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Introduction

The triple junction at the confluence of Admiralty Inlet, Possession Sound and the Main Basin region of Puget Sound contains a complex circulation pattern formed by tidal and estuarine circulation. The advective and mixing processes within this region are of particular interest to the siting a new municipal wastewater discharge north of Seattle. Eight lagrangian drifters were utilized to investigate the circulation within this region. The drifters are configured to telemeter a GPS position via both RF and ARGOS satellite service at a 30-minute interval. The trajectories obtained from a deployment of these drifters is compared to velocity predictions from a 3-D hydrostatic, sigma-coordinate model based on the Princeton Ocean Model (POM) that has been configured for the Puget Sound region. The model is configured on a 600x900m Cartesian grid and forced with river inflows, surface winds and tidal amplitudes. The usefulness of these data-model comparisons help in understanding the mean circulation and mixing processes within this system.

Triple Junction Region

Historical descriptions of the circulation within Puget Sound (Ebbesmeyer and Cannon 2001; Ebbesmeyer and others 1984; Cannon 1983) have documented its characteristics as a typical estuarine system. The river inflows, dominated by the Skagit and Snohomish rivers in Whidbey basin, mix with the ambient water, forming a fresher, less dense surface layer that flows out of the Sound. This water is compensated by dense, salty water flowing landwards at depth. Figure 1 illustrates this circulation, with the motion of the fresher surface water shown with solid arrows, and the denser bottom water shown with dashed arrows.

The triple junction region refers to the area south of Whidbey Island where Admiralty Inlet is connected to the Main Basin and Possession Sound, forming a ‘Y’ junction. Characteristic basin depths in this region are around 200m, with the exception of a large shoal south of Whidbey Island with a characteristic depth under 30m. Within this junction, the dense bottom water diverges to flow into the main basin and Whidbey basin, while the outflowing surface water converges to flow out Admiralty Inlet. The detailed flow pattern associated with how these flows converge and diverge within the triple junction region has not yet been described.

Lagrangian Drifters

The lagrangian approach of following a water parcel can be extremely valuable in understanding complex flow patterns. The ability to follow water parcels in a region of complex bathymetry can provide insight into the circulation patterns that a limited number of fixed current meters cannot.

The drifters used for this work were purchased from Seimac, Inc. (Halifax, Canada). The drifters consist of a surface buoy connected to a sub-surface drogue sail (Figure 2). The surface buoy contains a Global Positining Satellit system and a transmitter to relay the GPS coordinates through the ARGOS satellite or by radio frequency transmission. The ARGOS service will also locate the buoys by satellite triangulation, but these locations are less accurate than the GPS locations and were not used. The buoys were configured to obtain a GPS location every 30 minutes, and the last seven positions were recorded internally and transmitted when a satellite pass occurred. An unintended consequence of this configuration was the creation of data gaps when satellite passes were not sufficiently frequent. Typically, this resulted in six to 10 positions being lost per day. The subsurface drogue sail was similar to a holey-sock drogue, a fabric open-ended cylinder 10 meters long by 1.2 meters in diameter. The surface buoy can be released without the drogue sail in a weighted plastic barrel to follow water in the upper one meter.

These drifters have been deployed at 5 separate events with various the drogue depths, release times and locations. The conditions for each release are summarized in Table 1.

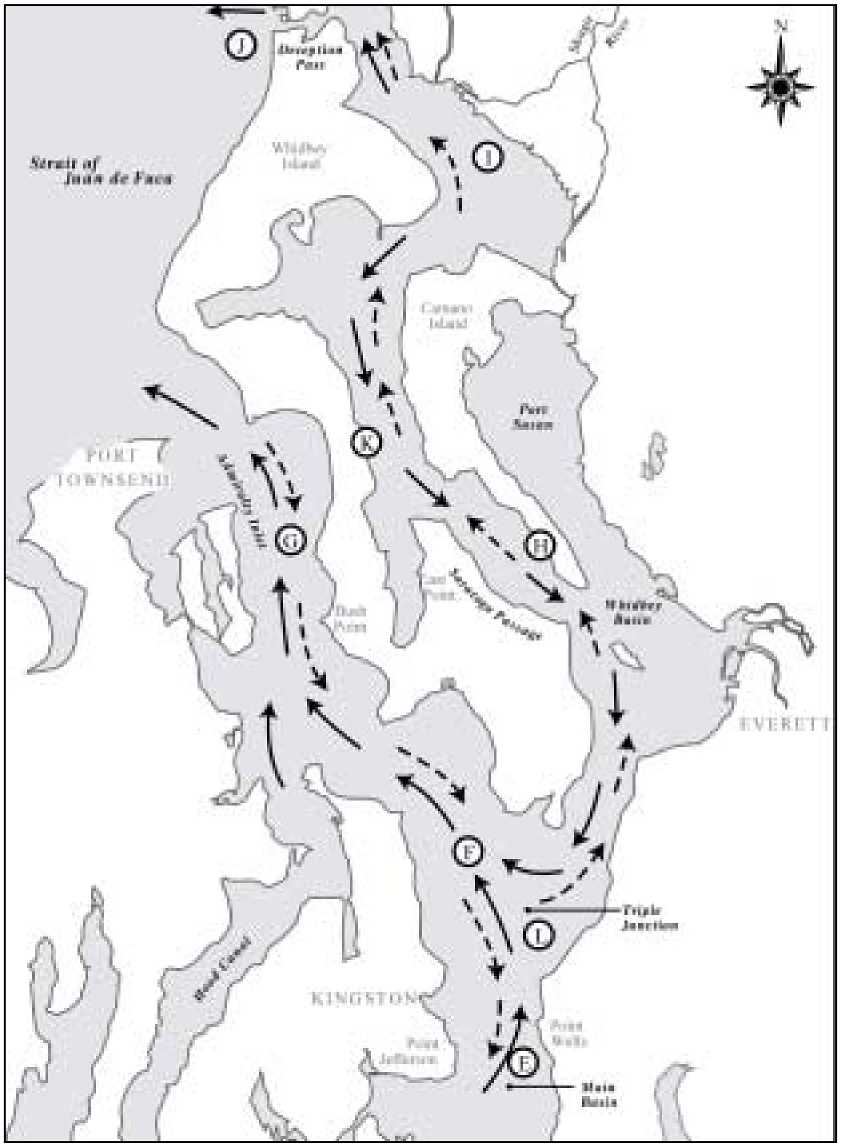

Figure 1 Estuarine Circulation in Puget Sound. The solid arrows indicate the fresher surface flow towards the ocean; the dashed arrows indicate the denser oceanic water moving landward. (E) Surface flow out of the Main Basin and South Sound; (F) upper layer outflow joined by outflow from Possession Sound; (G) sill separating Puget Sound from the Strait of Juan de Fuca; (H) surface outflow in Saratoga Passage; (I) surface water divergence between Skagit River's north and south forks; (J) net outflow from Deception Pass; (K) net inflow of bottom water in Saratoga Passage; (L) net bottom inflow flows south to main basin with a secondary fraction flowing northward.

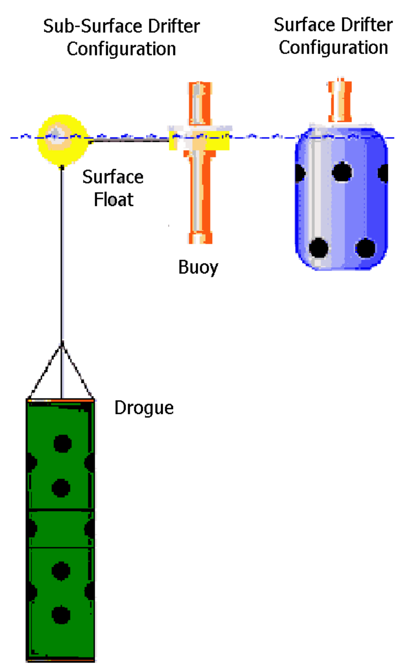

Figure 2 Schematic of Drifter/drogue configuration. The buoy housed the GPS and communication electroni

Table 1. Conditions of the five drogue deployments, labeled A through E. The wind conditions are a gross summary of the prevailing wind during the duration of the deployment.cs.

Release	Number Deployed	Drogue Depth	Duration	Tidal Phase	Wind Conditions
A	**8**	**30-40 m**	**6 hours**	**Ebb**	**Calm**
B	**8**	**1 m**	**24 hours**	**Ebb**	**North ~5 knots**
C	**6**	**20-30 m**	**24 hours**	**Flood**	**North ~ 5 knots**
D	**7**	**20-30 m**	**6 days**	**Flood**	**North 1.5d @ 5 kn South 2d @ 10 kn North 2d @ <5 kn**
E	**8**	**20-30 m 100-110 m**	**6 days**	**Ebb**	**South 3d @ 10 kn North 3d @ 10 kn**

The initial drogue deployments were reasonably short in duration, up to 24 hours, and were very useful in developing a methodology for deploying and retrieving the drogues. Deployments D and E, both six days in duration, provide a longer record of the advective patterns within the Triple Junction region. In both of these deployments, drogues were released at four positions, roughly equally spaced, about 1 mile off the eastern shore, denoted by the black squares in Figures 3 and 4. Four of the drifters where released at these locations during Release D, while the other four drifters were released at inshore locations, and are not shown. Two drogues were released at each of these four locations in Release E, one with a drogue sail 20 - 30m below the surface, the other 100-110m down. Deployments D and E occurred a month apart during the fall of 2000.

The trajectories of the four deeper drifters (100-110m) in Release E are illustrated in Figure 3. Over the duration of the release, the three northern drifters moved towards Admiralty Inlet, and all three appear to have grounded along the eastern side of the shoal that extends south of Whidbey Island. The blue contour line in Figure 3 corresponds to 110m, the depth that the drogue sails touch bottom. The fourth, and southernmost drifter also appears to have run aground at certain points. Despite this, the drifter moved across the basin, northward, back across the basin, and southward almost to its release position. Neither this type of motion, nor the motion of the northern three drogues would be expected from the classical estuarine circulation patterns. One might have expected a mean southerly movement with superimposed tidal oscillations, or the northern drifters moving in the mean north into Possession Sound. The substantal cross-channel motion of the drifters, and the large non-tidal motion of the southern drifter illustrate just how complex the motion within this region is.

The trajectories of the four drogues deployed in Release E with drogue sails 20-30m below the surface (Figure 4a) are significantly different from the deeper drifters and the four drogues released during Release D. The trajectories for the drogues at 20-30 m are shown in Figures 4a (Release E) and 4b (Release D), illustrating a dramatic variation in the current patterns between these two experiments, one month apart.

Similar to the deeper drifters in Release E, the 20-30m drifters tended to move across the channel. The middle two drogues drifted towards Admiralty Inlet (north-west), the same general motion as the deeper drifters released at these two locations. However, the northernmost and southernmost drifters did not follow their deeper counterparts. The northernmost drogue moved south and then eastward before grounding along the eastern shore, while the southernmost drogue drifted to the north before getting grounded along off Edmonds before finally drifting to the west.

In contrast to these trajectories, the drogues deployed during Release D tended to move along the underlying channel, with little cross-channel motion. These drifters had drogue sails set 20-30 m below the surface, and one drogue moved out through Admiralty Inlet, in accordance with the expected estuarine circulation. The other three drogues moved northward for about the first four days, against the expected surface flow out of Possession Sound. Two of the drogues passed to the north of Mukilteo before reversing direction and moving back south. The along-channel motions of these drifters illustrate that significant temporal variation can exist in the overall circulation. The likely contributors to this variability, wind and dense water intrusion events have been investigated (Matsuura and Cannon 1997; Bretschneider and others 1985), but not in relation to the circulation within the Triple Junction.

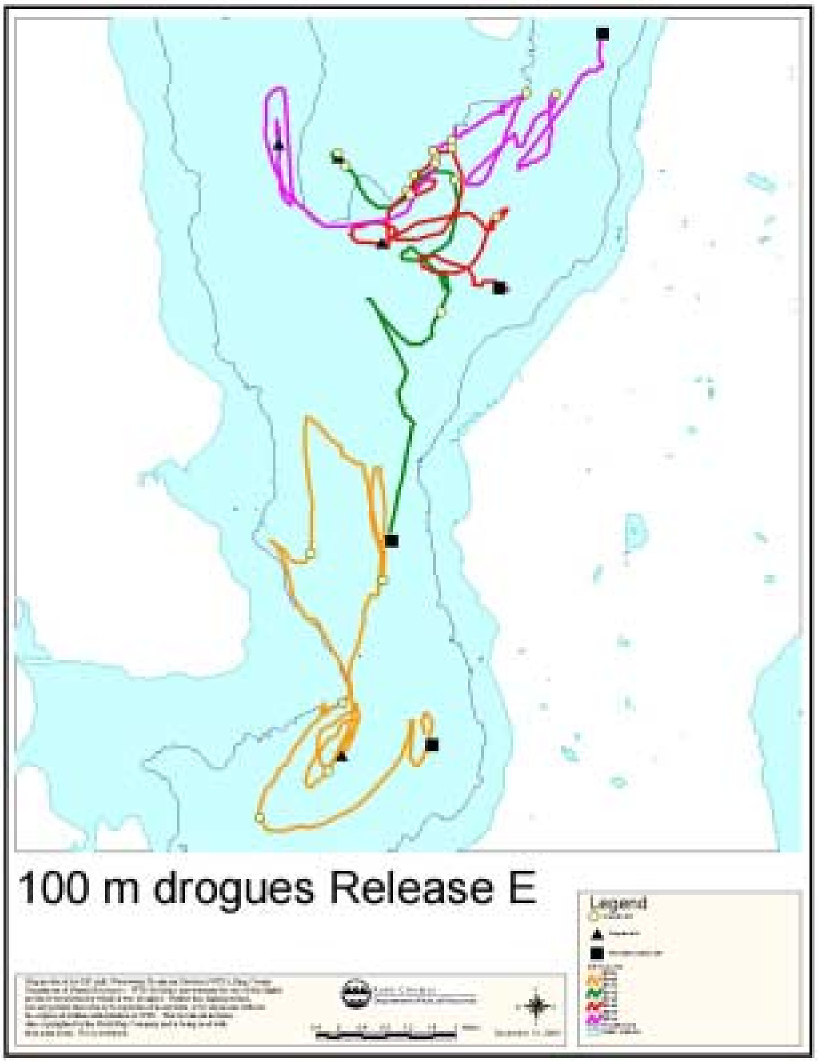

Figure 3 Drogue paths from Release E. During this release, the wind was from the South for the first 3 days at about 10 knots, then reversed to the South for the remaining 3 days. The deployment locations of the drogues are marked with black squares, their retrieval locations with black triangles. The yellow circles mark the drogue positions every 24 hours after release.

Numerical Model

The numerical circulation model is based on the Princeton Ocean Model (POM, Blumberg and Mellor 1987), a three-dimensional, hydrostatic, primitive-equation model. Kawase (1998) describes the specific implementation of the model to Puget Sound. The model consists of a cartesian grid covering the entire Puget Sound Region, including parts of the Strait of Juan de Fuca at a 600-m resolution in the east-west direction and a 900-m resolution in the north-south direction. The vertical co-ordinates are sigma, or terrain following coordinates. This implementation uses six layers, clustered near the surface, to discretize the vertical extent. The model is forced along the open boundary in the SJF with seven tidal constituents (M2, K1, S2, N2, O1, P1, M4), as well as wind stress along the surface and fresh water input.

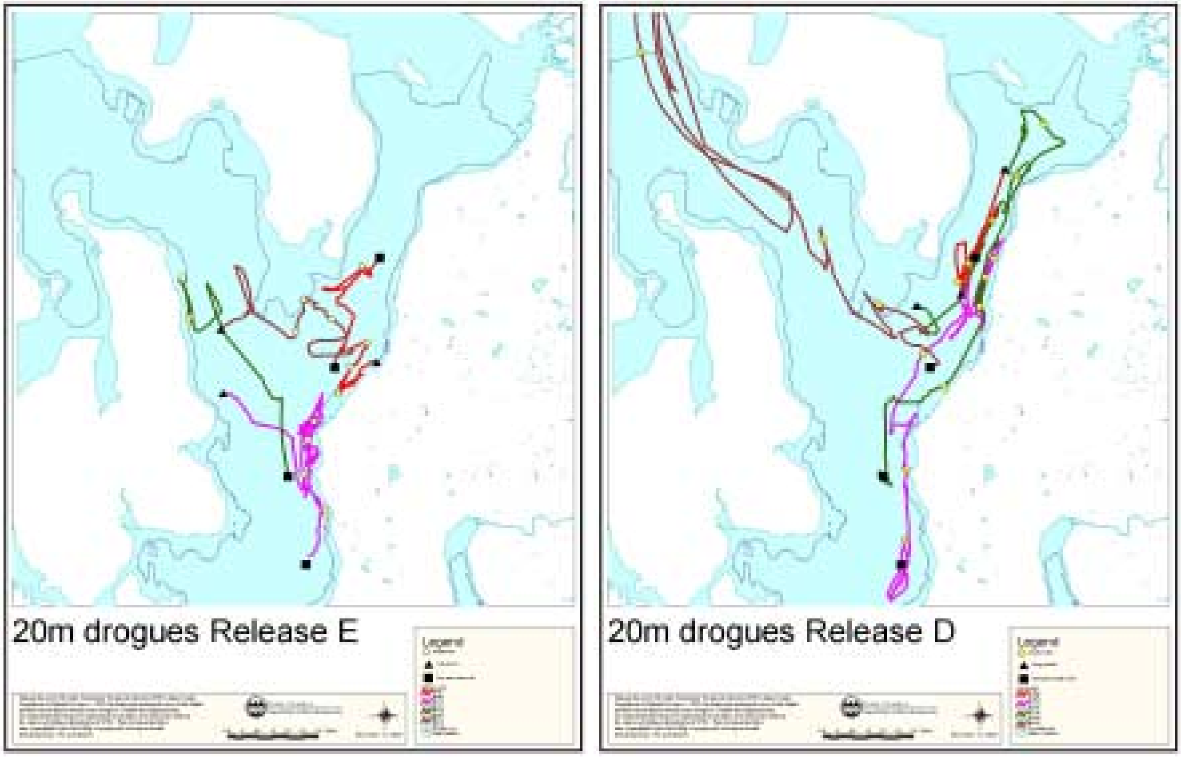

Figure 4 Drogues at 20-30 m depth during releases E and D. The deployment locations of the drogues are marked with black squares, their retrieval locations with black triangles. The yellow circles mark the drogue positions every 24 hours after release.

Observation-Model Comparison

In an effort to evaluate the numerical model's performance, we compare the predicted velocities with the displacement of the drogues over each half-hour time interval. The model was initialized with a typical winter density stratification. The model was then spun up from the beginning of year 2000 through the end of drogue release D, about 300 days. During this time, the model was forced with daily fresh water flows corresponding to the 14 major rivers. The free surface received wind, temperature, precipitation/evaporation, and short wave radiation fluxes on an hourly timestep. These fluxes were applied uniformly over the model domain.

At the start of drogue release D, 300 days after model initialization, the model velocity field was output at half-hour intervals matching the reported drogue positions. The velocity field was interpolated to each drogue position at the mean drogue depth (-25 meters). Figure 5 shows the predicted model velocities for four of the drogues, at different locations around the north main basin of Puget Sound. In these figures the model velocity, shown as the black arrows, is scaled such that the tip of the arrow should align with the next drogue position.

There are several common aspects between the observations and predicted velocities that can be seen in these figures. First, the model does, in general, align with the paths traced out by the drogues. Second, the modeled velocity tends to lag the drogue's trajectory. This is evident in Figure 5 as the drogue reverses direction, while the model velocities indicate it should continue its original motion.

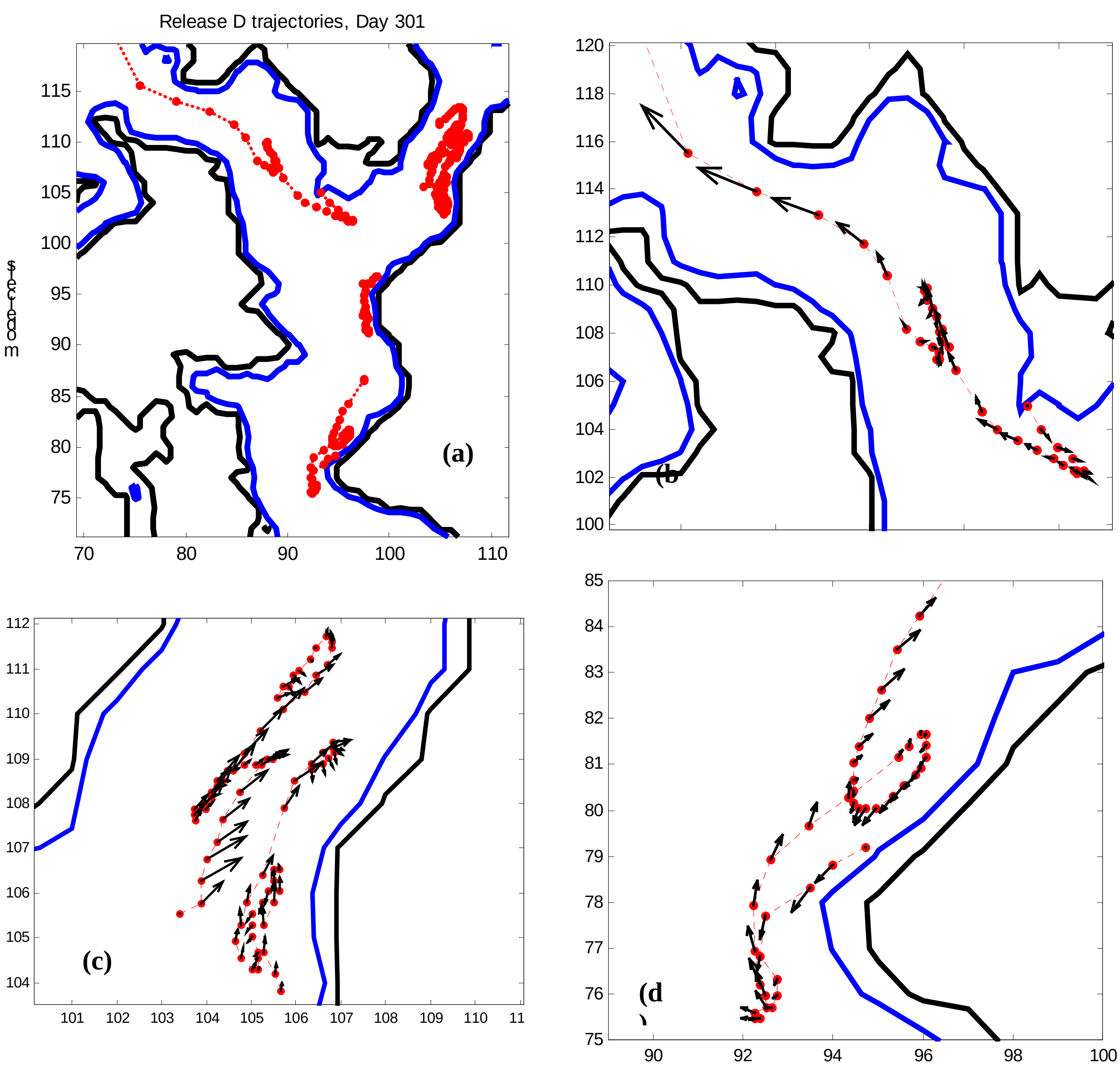

Figure 5. (a) Drogue paths of 5 drifters for a 24-hour period during Release D (Julian Day 301). (b-d) Comparison between the observed drogue trajectories (red dots) and the modeled velocities (black arrows). The velocity vectors are scaled such that the black arrow tips will align with the next observation (red dot) for no prediction error. (b) model velocities along drogue trajectory in Admiralty Inlet. (c) model velocities along two drogue trajectories in Possession Sound. (d) model velocities along drogue trajectory off West Point. The comparison for the drogue off Edmonds is not shown.

A comparison of the predicted and observed tides at Seattle show that the model tide is in close agreement with a composite tide predicted from the same 7 tidal constituents used to force the model (rms error = 6.2 cm). However, the model lags the observed tide by about an hour resulting in a poorer agreement (rms error = 37 cm). Thus, a portion of the disagreement between model and drogues may be attributed to the use of only seven tidal harmonics.

The direct comparison between model and drogue velocities is shown in Figure 6. Model and observed velocities are generally correlated, with an R^2 of 0.63. There appears to be moderate agreement here, with a tendency for the model to underpredict the observed velocities, particularly at higher speeds. No bias in direction (Figure 6b) is apparent, with a distribution of the errors in direction centered about zero. There are two clusters of errors close to +/- 180 degrees, indicative of the phase error that was noted earlier.

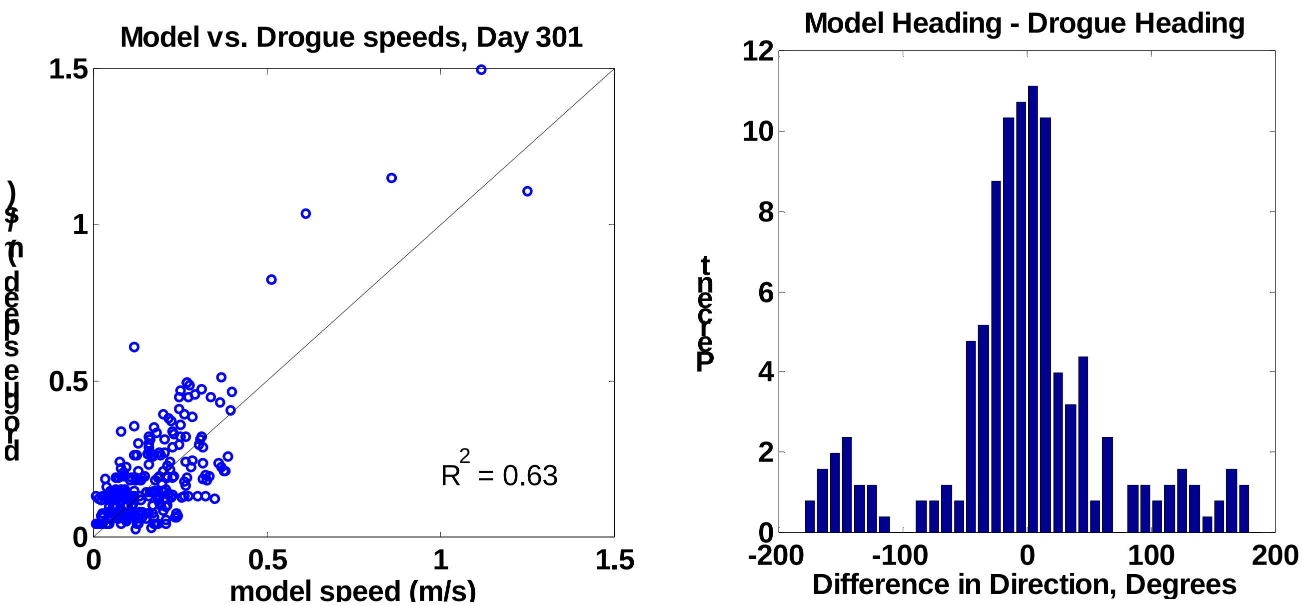

Figure 6 Comparison of observed drogue and predicted model (a) speeds and (b) directions for a 24-hour period during Release D. This is the period for which the five drogues are shown in Figure 5a.

Conclusions

The use of Lagrangian drifters, or drogues, has been very useful in illustrating the variability of currents within the Triple Junction region. The significant cross-channel motion and temporal variability shown by the drogues has demonstrated that the currents in region are more complex than a simple understanding of the estuarine circulation would explain.

The currents predicted from a numerical simulation show general agreement with the drogue trajectory observations. The model tended to be slightly out of phase with the drogue observations, resulting in a mode of vectors out of phase with the observations. This phase difference may have also contributed to the mismatch between the observed and predicted current speeds. In general, the model was in general agreement, but tended to underpredict the observed current speed. Some of these errors may be a result of omitting tidal harmonics within the model, or indicative of the need for additional model calibration. These items are currently being pursued to attempt to reduce these discrepancies. This method of comparison can provide an easily interpreted visual graphic, as well as enabling comparison of the numerical model at multiple spatial locations.

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References

Blumberg, A.F., and Mellor, G.L. 1987. A description of a three-dimensional coastal ocean circulation model. in Three-Dimensional Coastal Ocean Models, Vol.4, N. Heaps, Ed., American Geophysical Union, Washington, D.C. 208 pp.

Bretschneider, D.E., Cannon, G.A., Holbrook, J.R., and Pashinski, D.J. 1985. Variability of subtidal current structure in a fjord estuary: Puget Sound, Washington. J. Geophys. Res., **90**: 11949-11958.

Cannon, G.A. 1983. An overview of circulation in the Puget Sound estuarine system. NOAA Technical memorandum ERL PMEL-48, 30 pp.

Ebbesmeyer, C.C., and Cannon, G.A., 2001. *Review of Puget Sound Physical Oceanography related to the Triple Junction Region.* Report for King County Department of Natural Resources, 34 pp.

Ebbesmeyer, C.C., Coomes, C.A., Cox, J.M., Helseth, J.M., Hinchley, L.R., Cannon, G.A., and Barnes, C.A. 1984. Synthesis of current measurements in Puget Sound, Washington – Volume 3: Circulation in Puget Sound: An interpretation based on historic records of currents. NOAA Technical Memorandum NOS OMS-5, p3 pp. & 1 microfiche.

Kawase, M. 1998. A Numerical Model of Puget Sound Circulation. in Puget Sound Research ’98 Proceedings, Puget Sound Water Quality Action Team, Olympia, WA., 209-216.

Matsuura, H., and Cannon, G.A. 1997. Wind effects on sub-tidal currents in Puget Sound, J. Oceanogr., **53**: 53-66.